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SUMMARY

An experimental study was conducted to determine the time required for the liquid-vapor interface to reach equilibrium in spherical, cylindrical, and annular tanks. The results of this study established a functional dependence of the time to reach equilibrium on the pertinent liquid parameters and system dimensions expected to influence the time response of the interface. The form of the equation that results, as determined from the experimental data, verifies the Weber number scaling parameter.

INTRODUCTION

The NASA Lewis Research Center is currently conducting a study to determine the behavior of rocket engine propellants stored in space vehicle tanks while exposed to weightlessness (zero gravity) during coasting periods. In order to solve many of the problems that will be encountered in design of space vehicles, a knowledge of the zero-gravity equilibrium configuration of the liquid-vapor interface, the time required for the system to reach that equilibrium configuration, and the stability of the system is required. The liquid and vapor could, of course, be positioned by means of acceleration fields such as spinning the tank or accelerating (collection) rockets, but these methods may require relatively high energy levels or could be otherwise undesirable, especially for large vehicles. The proper employment of the surface energy properties of the solid-liquid-vapor system itself through the use of proper tank geometry would be more desirable.

The behavior of typical wetting and nonwetting liquids in spherical, cylindrical, and conical glass tanks has been studied in a drop-tower, zero-gravity facility. The results of these studies, presented in references 1 to 3, allow the prediction of the equilibrium liquid-vapor interface configuration during weightlessness as a function of container geometry, liquid properties, and contact angle. Also, an investigation into the capillary rise in tubes during weightlessness (ref. 4) led to a verification of the theory that solid-liquid-vapor systems tend toward a minimum-surface-energy configuration when the force of gravity is removed from the system. The hydrostatic stability characteristics of the liquid-vapor interface when subjected to acceleration disturbances were also investigated (refs. 5 and 6). The results indicate that the Bond number criterion, a dimensionless parameter consisting essentially of the ratio of acceleration to capillary forces, is valid for predicting the regions of hydrostatic stability of the liquid-vapor interface.

The time required for the solid-liquid-vapor system to reach its zero-gravity equilibrium configuration has been studied analytically by many investigators. The analyses of references 7 and 8 are typical of such studies wherein the time response of a deformed liquid drop (a liquid-vapor system) under the action of capillary forces was analytically determined. Of most interest to the space vehicle designer, however, are solid-liquid-vapor systems where the zero-gravity equilibrium configuration in the propellant tanks is generally a liquid-wetted tank wall (typical of most propellants with a 0° contact angle). The scaling parameter expected to define the time required for the solid-liquid-vapor system to reach its zero-gravity equilibrium configuration is the Weber number (We). This scaling parameter, consisting essentially of the ratio of inertia to capillary forces, is defined as

$$We = \frac{\rho}{\sigma} V^2 L \tag{1}$$

where ρ is the density of the liquid, V is the characteristic velocity, L is a characteristic dimension of the system, and σ is the surface tension of the liquid. A general expression for the time T required for the interface to reach its equilibrium configuration can be derived from the Weber number by substitution of length divided by time:

$$T = \frac{1}{We^{1/2}} \left(\frac{\rho}{\sigma}\right)^{1/2} L^{3/2} \tag{2}$$

This expression bears great resemblance to the results of the aforementioned analyses in references 7 and 8.

It should be noted that equation (2) does not take into account the retarding effect of viscosity on the time required to reach equilibrium. The analysis of reference 8 indicates that the effect of viscosity can be neglected as long as one deals with liquid masses whose linear dimensions are much greater than 1 micron.

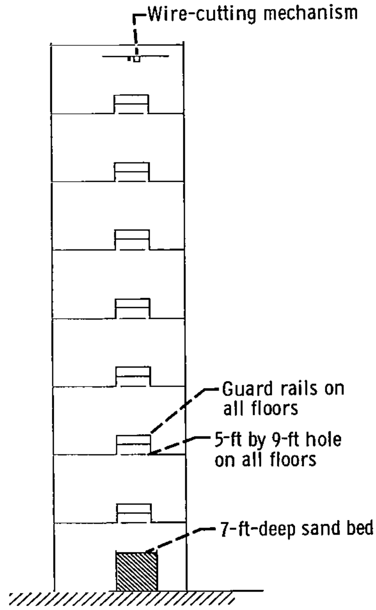
The purpose of this report is the presentation of the results of an experimental investigation to determine the time required for the liquid-vapor interface to reach its zero-gravity configuration after entering a weightless environment and to determine the scaling law that allows prediction of the phenomenon for full-size space-vehicle tanks. This experimental study was conducted in a drop tower for spherical, cylindrical, and annular glass tanks and liquids with a 0° contact angle on glass.

APPARATUS AND PROCEDURE

Drop-Tower Facility

The experimental results were obtained in the 100-foot zero-gravity, drop-tower facility at the Lewis Research Center. A photograph of the drop tower and a schematic drawing showing pertinent details are presented in figure 1.

(a) Exterior view.



(b) Schematic drawing.

Figure 1. - 100-Foot drop-tower facility.

Initiation of zero gravity (free fall) is accomplished by the activation of a compressed-air release mechanism at the roof of the tower that causes the failure of a strand of music wire from which the experiment is supported prior to dropping. Termination of zero gravity occurs when the experiment reaches the first floor of the tower where it is decelerated in a 7-foot-deep bed of sand. The actual free-fall distance is 85 feet, yielding a 2.25-second period of zero-gravity time. Air drag on the experimental package is kept below 10^{-5} g by allowing the experiment to free fall inside an air drag shield. A more detailed description of the facility is given in references 1 and 2.

Experiment Package

A photograph of the experimental package used for this investigation is presented in figure 2. This package consists essentially of a 16-millimeter high-speed motion-picture camera and a dull white box indirectly illuminated by four 20-watt light bulbs in which the tank and test liquid under investigation were mounted. Electric power for the camera and the lights is carried on

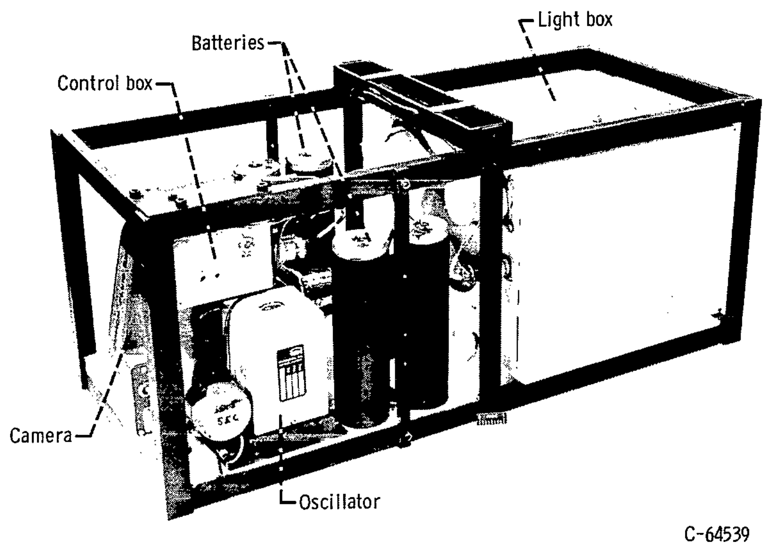


Figure 2. - Experimental package showing component locations.

board the package in the form of rechargeable nickel-cadmium batteries.

Experimental Tanks and Test Liquids

Spherical, cylindrical, and annular glass tanks were used in this experimental study. The inside diameters of the spherical tanks were 4.7, 7.4, and 9.8 centimeters. The inside diameters of the cylinders were 2.2, 3.8, 8.0, and 15.6 centimeters. The ratios of inner to outer tank diameter for the annular tanks were nominally one-fourth, one-half, and three-fourths, where the absolute values of the diameters of the outer tanks were 8, 12, and 15.6 centimeters.

The purity-certified liquids used in this investigation were 200 proof ethanol, carbon tetrachloride, and a volumetric solution of 9.1 percent ethanol and 90.9 percent distilled water. These liquids were chosen because they have a 0° contact angle with the glass tanks and provide a range in the ratio of density to surface tension. The pertinent physical properties of the test liquids are given in the following table:

Property	Ethyl alcohol	Carbon tetrachloride	90.9 Percent water and 9.1 percent ethyl alcohol[a]
Density at 20° C, g/cm^3	0.7893	1.595	0.9843
Surface tension at 20° C in air, dynes/cm	22.3	26.8	50.24
Ratio of density to surface tension, sec^2/cm^3	.0354	.0595	.0196

[a]Percent by volume.

Cleaning Procedure

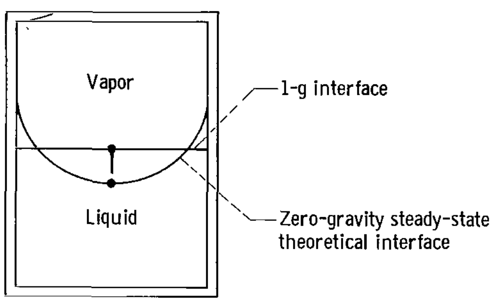
Contamination of all the surfaces that came in contact with the test liquids that could alter the surface tension and contact angles of the test liquids was carefully avoided. The glassware used in the investigation was immersed in heated chromic acid, cleaned ultrasonically in a detergent and distilled water solution, rinsed thoroughly with distilled water, and finally dried with warm air. The acrylic plastic used to support the inner wall of the annular tanks was cleaned by using the same procedure except that the immersion in chromic acid was omitted.

RESULTS

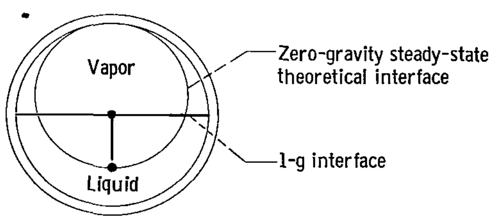
Definition of Time to Reach Equilibrium

The solid-liquid-vapor systems studied in this investigation exhibit characteristics typical of under-damped systems; that is, the liquid-vapor interface oscillates about its steady-state configuration (see ref. 1). Because the zero-gravity test time attainable in the 100-foot drop tower is relatively short (2.25 sec), it is, in general, insufficient to observe the complete decay of the oscillations of the liquid-vapor interface, especially for the larger tank sizes studied. As a result of this limited zero-gravity test time and the oscillations of the liquid-vapor interface, a definition of time to reach equilibrium has been formulated based, in essence, on the first pass of an under-damped system through its steady-state position. Because the zero-gravity configuration of the interface is a function of the shape of the container, the definition of the time to reach equilibrium for each of the tank shapes studied is now given.

Cylinders. - Presented in figure 3(a) is the 1-g configuration and the zero-gravity steady-state theoretical configuration of the liquid-vapor interface for a liquid with a 0° contact angle. The time to reach equilibrium was selected to be the time for a point on the 1-g interface (lying on the vertical centerline of the tank) to traverse the straight-line distance to its perpendicular projection on the zero-gravity steady-state theoretical interface. This definition does not imply that the entire liquid-vapor interface be in its zero-gravity steady-state theoretical configuration when this point reaches its specified location on the zero-gravity steady-state theoretical interface.



(a) Cylindrical tank.



(b) Spherical tank.

Figure 3. - Schematic drawing of 1-g and zero-gravity steady-state interface configurations for liquid with 0° contact angle.

Spheres. - Presented in figure 3(b) is the 1-g configuration and the zero-gravity steady-state theoretical configuration of the liquid-vapor interface for a liquid with a 0° contact angle. The time to reach equilibrium was selected to be the time for a point on the 1-g interface (lying on the vertical centerline of the tank) to traverse the straight-line distance to its perpendicular projection

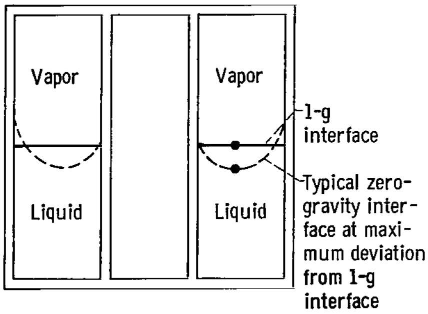


Figure 4. - Schematic drawing of 1-g and zero-gravity interface configurations in annular tank for liquid with 0^0 contact angle.

on the zero-gravity steady-state theoretical interface. This definition does not imply that the entire liquid-vapor interface be in its zero-gravity steady-state theoretical configuration (that is, that the liquid completely wets the tank walls) when this point reaches the specified location on the zero-gravity steady-state theoretical interface.

Annuli. - Unfortunately, in establishing a criterion for the time to reach equilibrium in annular tanks, no experimental data exist that clearly establish the steady-state theoretical shape of the liquid-vapor interface. As a result of this lack of data, the criterion for annular tanks has been modified as follows from the criteria established for spherical and cylindrical tanks. The time to reach equilibrium for annuli is defined as the time required for a point on the 1-g interface to traverse the straight-line distance along the perpendicular projection to the point of maximum deviation of the zero-gravity interface from the 1-g interface (see fig. 4).

Data for Spherical Tanks

The results of the investigation to determine the time required for the liquid-vapor interface to reach its equilibrium configuration is presented in figures 5 and 6. Plotted in these figures is the time to reach equilibrium as a function of the diameter of the spherical tank (fig. 5) and as a function of the ratio of density to surface tension (fig. 6). A parameter that was held constant during the experimental study was the ratio of the liquid volume to tank volume (50 percent). As reported in reference 1, the time to wet the tank wall completely is dependent on this ratio in spherical tanks to the extent that shorter times are required at volume ratios greater than 50 percent, and longer times are required at volume ratios less than 50 percent. For this investigation, however, it was felt that the data at the 50 percent ratio would be representative of the time to reach equilibrium in spherical containers.

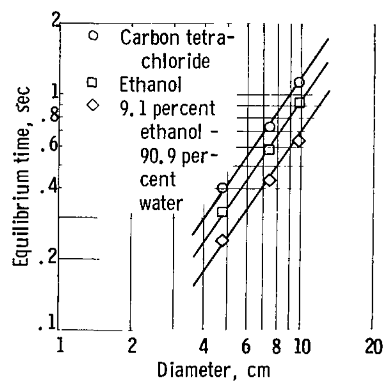


Figure 5. - Effect of tank size on time to reach equilibrium in 50-percent-full spheres.

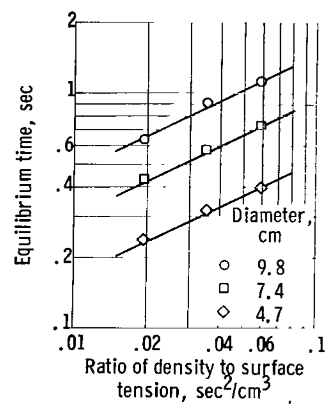


Figure 6. - Effect of liquid properties on time to reach equilibrium in 50-percent-full spheres.

It should be noted that, in spherical tanks, the configuration of the liquid-vapor interface at the time of measurement of the time to reach equilibrium is significantly different from the configuration labeled zero-gravity

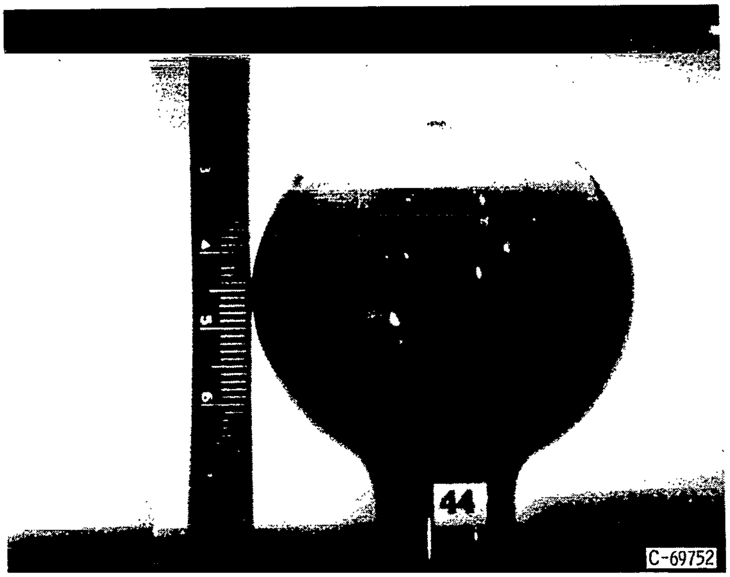


Figure 7. - Typical configuration of interface at time of measurement in spherical tank.

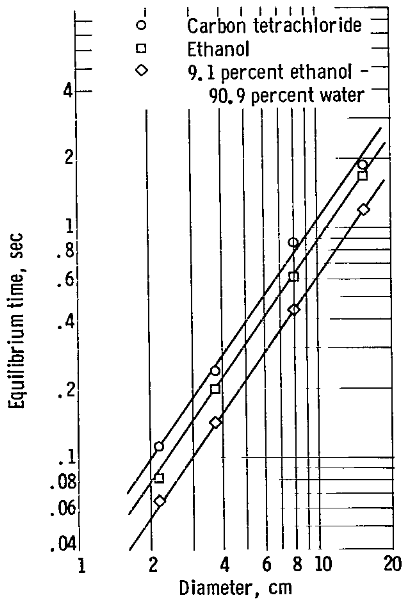


Figure 8. - Effect of tank size on time to reach equilibrium in cylinders.

steady-state theoretical interface in figure 3(b) because the entire wall of the container had not as yet become totally wetted. The point on the liquid-vapor interface at the centerline of the tank, however, has traversed the distance specified by the previous definition of time to reach equilibrium. Presented in figure 7 is a selected photograph that illustrates the configuration of the interface at the time of measurement. The photograph was taken from the motion picture data obtained during one test drop.

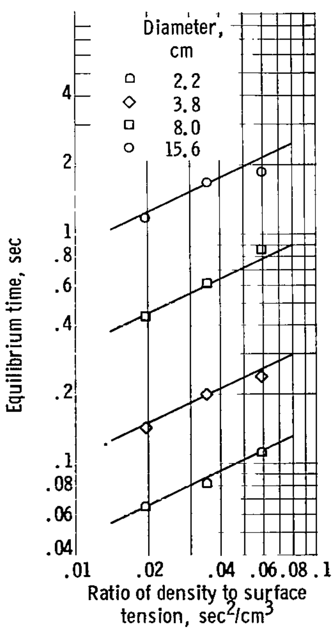


Figure 9. - Effect of liquid properties on time to reach equilibrium in cylinders.

Data for Cylindrical Tanks

The results of the investigation to determine the time required for the liquid-vapor interface to reach its equilibrium configuration is presented in figures 8 and 9. Plotted in these figures is the time to reach equilibrium as a function of the diameter of the cylindrical tank (fig. 8) and as a function of the ratio of density to surface tension (fig. 9).

Again, the configuration of the liquid-vapor interface at the time of measurement of the time to reach equilibrium is somewhat different from the steady-state theoretical zero-gravity configuration illustrated in figure 3(a). The difference, however, is not as severe as that observed in the spherical tanks. Shown in figure 10 is a typical photograph that illustrates the interface configuration at the time of measurement.

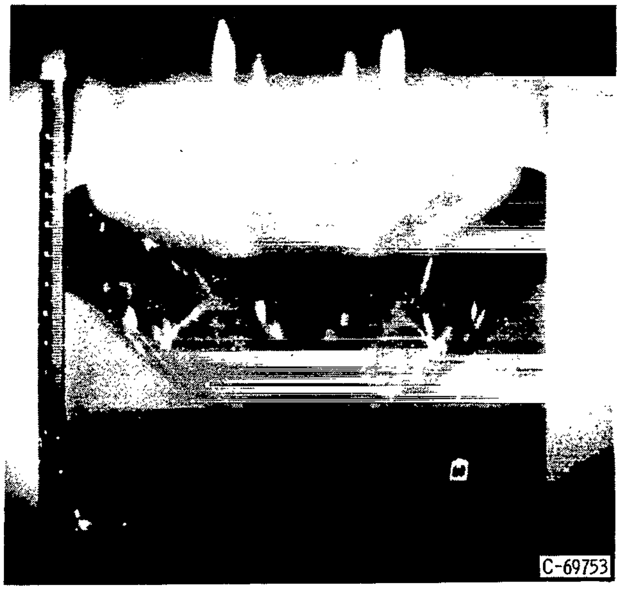


Figure 10. - Typical configuration of interface at time of measurement in cylindrical tank.

Data for Annular Tanks

The results of the investigation to determine the time required for the liquid-vapor interface to reach its equilibrium configuration is presented in figures 11 and 12. Plotted in these figures is the time to reach equilibrium as a function of the diameter of the outer wall of the tank (fig. 11) and as a function of the ratio of density to surface tension for annuli of 1/2 diameter ratio (fig. 12). A photograph showing a typical configuration of the liquid-vapor interface at the time of measurement is presented in figure 13.

It is noted that at a diameter ratio of 3/4, only one data point was obtained for each test liquid studied (see fig. 11). This minimum amount of experimental data is caused by the fact that, at absolute outer diameter values less than approximately 16 centimeters, meaningful data are unattainable due to the small distance between the inner and the outer walls of the annular tank.

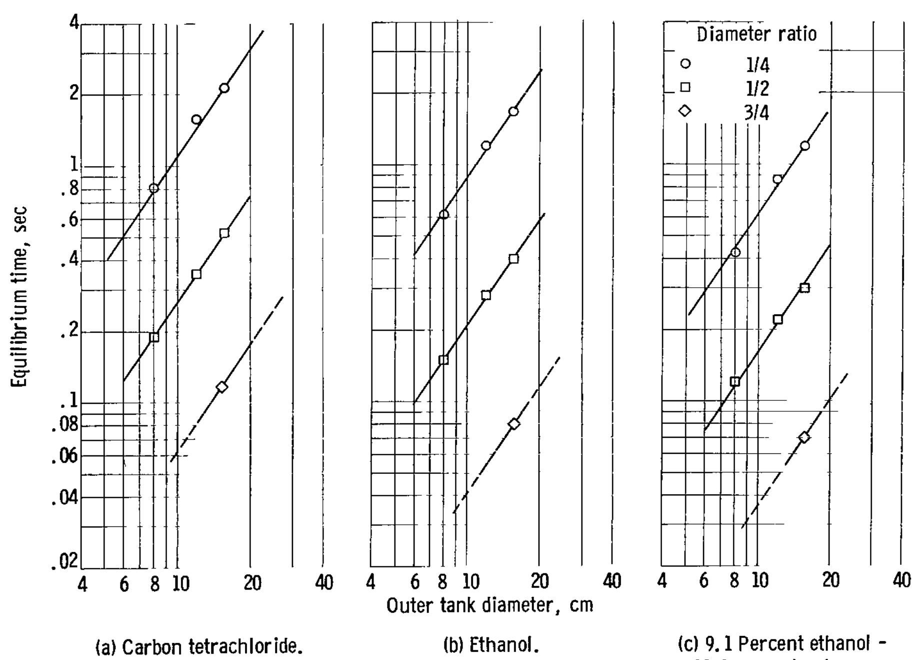


Figure 11. - Effect of tank size on time to reach equilibrium in annuli.

DISCUSSION OF RESULTS

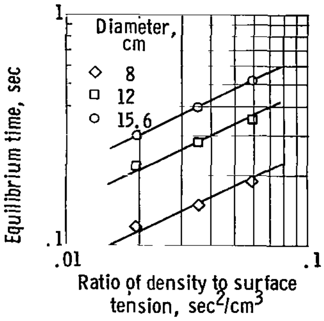


Figure 12. - Effect of liquid properties on time to reach equilibrium in annular tanks with diameter ratio of 1/2.

Verification of Weber Number Scaling Parameter

The results of the experimental study of the time required for the liquid-vapor interface to reach equilibrium in spherical, cylindrical, and annular tanks (figs. 5 to 12), establish a functional dependence of the time to reach equilibrium on the pertinent liquid parameters and system dimensions that are expected to influence the time response of the interface. The form of the equation that results from the functional dependence of the time to reach equilibrium on the liquid parameters and system dimensions, as determined from these data, verifies the Weber number scaling parameter and is

$$T = K(\rho/\sigma)^{1/2}(D)^{3/2} \qquad (3)$$

where K is an empirical constant related to $(We)^{-1/2}$, ρ is the density of the liquid, σ is the liquid-vapor surface tension, and D is the diameter of the tank. The constant and the exponents were obtained from the slope and the intercept of the curves of figures 5 to 12.

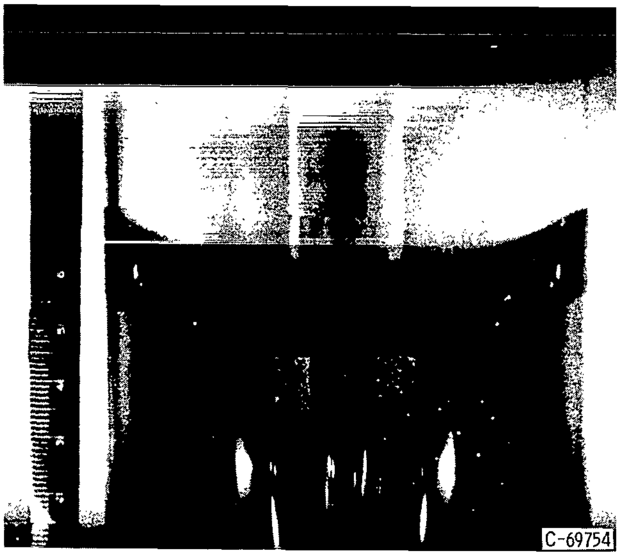


Figure 13. - Typical configuration of interface at time of measurement in annular tank.

Tank geometry	Empirical constant, K
50-Percent-full sphere	0.158
Cylinder	.146
1/4 Diameter ratio annulus	.146
1/2 Diameter ratio annulus	.035
3/4 Diameter ratio annulus	.007

The actual value of the constant K was found to be a function of the geometry of the solid-liquid-vapor system. Hence, for this investigation five different values of K (or Weber number) were obtained. These values are presented in the table at the left.

Application of Weber Number Scaling Parameter

As a result of this investigation, it is now possible to predict the time to reach equilibrium of the liquid-vapor interface in full-size space-vehicle tanks. Presented in figure 14 is a plot of the time to reach equilibrium in spherical and cylindrical tanks for one value of the ratio of density to surface tension against

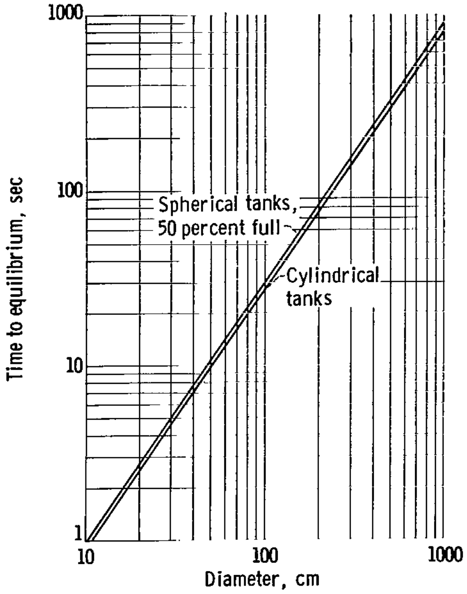


Figure 14. - Time required for liquid-vapor interface to reach equilibrium for spherical and cylindrical space-vehicle tanks. Ratio of density to surface tension, 0.0354 second^2 per centimeter^3.

the diameter of the tank. The curve was obtained by applying the Weber number scaling parameter to extend the data obtained in the present study to tank diameters currently under consideration for space vehicles.

It can be seen from an examination of figure 14 that, for space-vehicle tanks of the order of 20 feet in diameter (approximately 610 cm), times of 390 and 430 seconds are required for the liquid-vapor interface to form its equilibrium configuration after entering weightlessness in cylindrical and spherical tanks, respectively.

SUMMARY OF RESULTS

An experimental investigation of the time required for the liquid-vapor interface to reach equilibrium after entering a weightless environment yielded the following results:

1. The Weber number criterion, consisting essentially of the ratio of inertia to capillary forces, is valid for predicting the time to reach equilibrium.

2. An empirical constant that is proportional to the Weber number was determined for spherical, cylindrical, and annular tanks.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, June 8, 1964

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